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Challenges in reducing the computational time of QSTS simulations for distribution system analysis

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Abstract

The rapid increase in penetration of distributed energy resources on the electric power distribution system has created a need for more comprehensive interconnection modelling and impact analysis. Unlike conventional scenario-based studies, quasi-static time-series (QSTS) simulations can realistically model time-dependent voltage controllers and the diversity of potential impacts that can occur at different times of year. However, to accurately model a distribution system with all its controllable devices, a yearlong simulation at 1-second resolution is often required, which could take conventional computers a computational time of 10 to 120 hours when an actual unbalanced distribution feeder is modeled. This computational burden is a clear limitation to the adoption of QSTS simulations in interconnection studies and for determining optimal control solutions for utility operations. Our ongoing research to improve the speed of QSTS simulation has revealed many unique aspects of distribution system modelling and sequential power flow analysis that make fast QSTS a very difficult problem to solve. In this report, the most relevant challenges in reducing the computational time of QSTS simulations are presented: number of power flows to solve, circuit complexity, time dependence between time steps, multiple valid power flow solutions, controllable element interactions, and extensive accurate simulation analysis.

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NOMENCLATURE

AMI	Advanced Metering Infrastructure
DER	Distributed Energy Resource
ESS	Energy Storage System
IEEE	Institute of Electrical and Electronic Engineers
NREL	National Renewable Energy Laboratory
OpenDSS	Open Distribution System Simulator™
p.u.	per unit
PV	Photovoltaic
QSTS	Quasi-Static Time-Series
SOC	State-of-charge

1. INTRODUCTION

The penetration levels of distributed energy resources (DERs) on distribution networks are quickly increasing, challenging the conventional planning and operation of the electric power system. Interconnection studies are required for the safe connection and operation of the resources. These studies determine the impacts of new DERs on a specific distribution feeder: voltage violations, component thermal overloads, power flow direction, system losses, excessive controller actions, etc. Conventionally, interconnection studies have been scenario-based, snapshot, static simulations under certain pre-determined conditions such as peak demand and nominal PV output. However, scenario-based studies cannot capture the impact of fast variations in power injection introduced by some DERs (e.g. PV or wind) and cannot model important effects such as the operation of controllers with delays nor the number of tap changer operations.

A draft of an IEEE standard discusses this need for a time-series simulation in interconnection studies [1]. Quasi-static time-series (QSTS) simulation chronologically solves static power flows based on historical time-series profiles [2], [3]. The benefits of this time-series simulation over scenario-based simulation are that it accurately simulates the conditions that a feeder will experience over the course of time, and scenario-based simulation cannot capture the time-dependent impacts (e.g. the number of controller actions) or the impact of power fluctuations [2]–[4].

The QSTS simulation chronologically solves static power flows at a specific time resolution for a given time-horizon. By solving them chronologically, a temporal dimension is created allowing time-dependent controllers (delays, hysteresis, etc.) to be captured in the simulation. The time resolution and horizon depend on the objective behind the interconnection study, the type of DER implemented, and the available historical data. For instance, system losses do not require high time resolution, while excessive controller actions require finer time-steps [5]. Similarly, the type of DER implemented can affect the distribution feeder differently based on its second to minute fluctuations – i.e. solar PV [6] vs. energy storage [7]. Lastly, the time resolution and horizon of a QSTS simulation can be dictated by the availability of historical data. Year-long datasets may not always be available for each load on a specific feeder. However, this limitation should quickly disappear as advanced metering infrastructure (AMI) data becomes broadly used.

Since distribution system controller delays are between 10 to 60 seconds, a time resolution of at least 10 seconds is used. In [5], a year-long time-horizon with a time step of 1 second is recommended to capture the interaction among all controllers, the PV profile, and the seasonal variation of the loads on the feeder. Such computation implies solving 31.5 million chronologically-dependent power flows. On traditional computers, the computational time of this simulation can reach 10-120 hours depending on the size and complexity of the feeder model. Simulating multiple sizes, locations, or configurations of DERs will correspondingly increase this computational time. Computational power limitations are therefore the main barrier to industry-wide use of QSTS simulations in interconnection studies and for determining optimal control solutions for utility operations. Thus, there is a need for reducing the computational time of QSTS simulations.

The computational time of QSTS simulations has not previously been a significant concern for applications that are only solving a couple days of the year or solving a yearlong simulation at hourly resolution. Despite the significantly improved accuracy, the computational burden of yearlong 1-second resolution QSTS simulations has been limited to academic researchers. In order to move high-resolution extended time-horizon QSTS simulation into commercial application and adoption by distribution planners, the computational time must be decreased. Additionally, with increasing numbers of smart grid devices, the number of QSTS simulations will continue to increase with combinations and permutations of settings (such as potential volt-var curves on advanced inverters) to perform Monte Carlo analysis and different optimization algorithms. Because QSTS is a relatively new field of research, the complexity of running QSTS simulation has not been discussed in detail in the literature. A recent publication discusses the motivation and requirements for QSTS for distribution system analysis but does not address the challenges of computational time reduction [5].

In this report, we discuss the challenges in reducing the computational time of QSTS simulations. In Chapter 2, the necessary background regarding QSTS simulations is discussed and a review of the literature addressing its computational speed is presented. Chapters 3 to 8 are devoted to addressing six major considerations that impact QSTS. Chapter 3 discusses the fact that the power flow solution can be very fast, but the difficulty is solving the power flow equations 31 million times for each second of the yearlong QSTS simulation. Chapter 4 presents the aspects of distribution system modelling that make the problem nonlinear, discontinuous, and unpredictable due to the circuit complexity. Chapter 5 introduces the challenge of time dependence between each power flow solution that requires QSTS simulations to be solved sequentially. Chapter 6 discusses the challenge of hysteresis and deadbands in distribution system controls that allow for several independent states. Chapter 7 shows how it can be challenging to model the interactions between different controllers and the cascading error that is caused by slight variations in models. Chapter 8 discusses the speed challenge created by logging massive amounts of data during a QSTS simulation and calculating accurate evaluation metrics. Lastly, the ongoing research to address these challenges is presented in Chapter 9.

2. BACKGROUND

2.1. QSTS Simulation

Realistically modeling a physical distribution feeder can be challenging when considering time-varying loads, controllable devices, and DER power injections. Since dynamic simulations are computationally cumbersome, the state of the system can be modelled with phasors in the frequency domain that vary over a time-horizon by repeatedly solving static power flows. Controllable devices on a feeder often operate based on the current or previous state of the system using an input signal (i.e. time or voltage signal). The controller logic of these devices can also be modeled in discrete time to include their time dependence nature. Thus, quasi-static time-series simulations step through discrete chronological time steps to realistically simulate the operation of a specific distribution feeder based on power injection profiles and feeder topologies while considering the time-dependent logic of controllable devices. At each time step, there are two main objectives: (1) solve the power flow equations to determine the voltage magnitude and angle at each node, and (2) determine whether a controllable device takes an action. These are repeated for each time step in chronological order over the time-horizon to capture the effect of controller delays and thresholds. Several metrics can be computed and analyzed at the end of the simulation to quantify power system behavior. A high-level diagram in Figure 1 shows the general concept of a QSTS simulation.

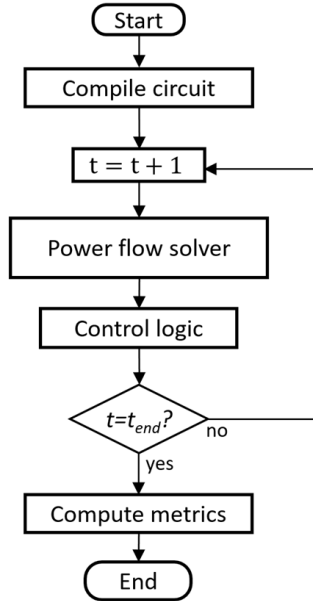


Figure 1. High-level diagram of a QSTS simulation.

Time-series datasets based on substation or AMI data can be used to model the loads through time. Similarly, irradiance data can be used to model the output of PV systems on the feeder. Using that data as load and PV profiles, a QSTS simulation can simulate the operation of a feeder realistically. The power flow on a distribution feeder is impacted not only by the set of power injections on it but also by any voltage regulating devices. Specifically, certain devices such as voltage regulating tap changers or capacitor banks will affect the voltage and thus, the

power flow on a feeder. The operation of these devices is often-based on local discrete controllers with delays and deadbands that requires to be modeled for the simulation. The interdependence between time-steps created by the hysteresis of the controllers requires the simulation to be solved chronologically. The challenges in modeling these controllers is discussed in Chapter 5, 6, and 7.

The purpose of running a QSTS simulation on a distribution feeder is to determine all the electric quantities at a given point in time (voltages, angles, current flows, tap positions, controller statuses, etc.) and more generally evaluate how a feeder would operate under different conditions, such as new control algorithms or a new PV interconnection. Several time-series impacts can be analyzed from a QSTS simulation including but not limited to:

- Excessive controller actions: certain controllable elements may or may not be affected. For instance, tap changers may see excessive operation due to the addition of PV systems on a feeder. Excessive controller actions can reduce equipment lifespan, resulting in higher operating costs.
- Voltage quality: Feeders can experience voltage extremes for sustained periods of time or experience undesired voltage fluctuation (flickering), potentially violating grid standards.
- System loss: Depending on the power flow on the circuit, line losses can differ.
- Power flow direction: Distributed DERs can create reverse power flow. The protection schemes and voltage regulating device controls must be adapted in consequence.
- Equipment loading assessment: Equipment such as distribution lines or transformers may experience excessive loading that can speed up equipment aging or even permanent damage.

Various metrics can be derived from these impacts based on the objective behind the interconnection study. The complexity of computing these metrics is discussed in Chapter 8.

2.2. Review of QSTS Speed Research

The single most important barrier to the mass adoption of QSTS simulations in interconnection studies is the computational burden associated with the simulation. Solving a set of unbalanced 3-phased nonlinear power flow equations at 1-second resolution for a year chronologically is especially challenging when a realistic distribution feeder is modeled. With a computational time between 10-120 hours for realistic feeders, running QSTS simulations for multiple feeder configurations or controller settings cannot be done on a single computer in a reasonable time period. Thus, QSTS simulations have been performed at larger time-steps or shorter time-horizons [5]. Minimal research efforts in the literature have been devoted to speeding up the computational time of QSTS simulations [8]–[11].

One method for increasing the computational speed is to reduce the size of the modeled distribution feeder. A method of reducing the number of buses on large feeders while maintaining the electrical characteristics of the system is proposed in [8] with minimal accuracy error on the preserved buses of interest. The size of the distribution feeder can also be reduced by separating geographical sections of the feeder into subnetwork and solving them in parallel on multicore machines using A-Diakoptics [9]. These approaches mostly focused on reducing the computational burden of the power flow solver, which then also make the QSTS simulation faster.

References [10] and [11] demonstrate that computational time can be reduced by reducing the number of power flow computations altogether. Time-steps throughout the year can be clustered into similar power flow scenarios to limit the number of computations of the power flow equations. Both approaches show very promising time reduction but not include the controller logic of voltage regulating devices.

As discussed above, limited efforts have focused on reducing the computational time of QSTS simulations. In order to provide the benefits of QSTS presented in the previous section, the simulation speed needs to be significantly improved orders of magnitude beyond previous research capabilities and the state-of-the-art. In the following sections, the different challenges regarding this research direction are discussed in detail and ongoing efforts are discussed in Chapter 9.

3. CHALLENGE 1: NUMBER OF POWER FLOWS TO SOLVE

3.1. Problem Statement

A yearlong QSTS simulation at 1-second granularity solves 31.5 million static power flows. No matter how fast the iterative algorithm is at solving the unbalanced three-phase nonlinear power flow equations, computing it 31.5 million times requires significant computational power.

3.2. Discussion

3.2.1. Speed of current power flow solvers

Iterative power flow solvers have been researched and implemented since the 1950s [12], [13]. They are at the core of numerous power system analyses; consequently, significant effort has been devoted to improve their simulation speed (i.e. reduce the number of iterations and accelerate each iteration) over the decades. Fast iterative algorithms for distribution systems are already implemented in commercial software like CYME and in open source packages like OpenDSS, or GridLAB-D.

Two directions can be taken in reducing the computational time of power flow solvers: the time it takes to solve the set of equations and the number of iterations it takes to converge. Various iterative techniques such as Newton-Raphson or Fixed Point method have been applied in the literature and in commercial programs to solve the power flow equations. Different power flow solution techniques may offer better computational time per iteration depending on the feeder characteristics and especially on how they are implemented in a specific coding language. Power flow approximations are a good way to reduce computational time (see sub-section 3.2.2).

On the other hand, significant computational time reductions of the iterative solver can be theoretically achieved by reducing the number of iterations, but progress in this direction has already been pursued and solvers have already been optimized to converge with a small number of iterations within the scope of QSTS simulations. This was tested in OpenDSS with a fast-varying PV profile and a slow-varying load profile. Each time-step of a yearlong QSTS simulation at 1-second granularity converged in 2.0080 iterations on average: one iteration to compute the solution and one to check if it converged [14]. Not only do current solvers quickly converge, the initial iteration uses the solution from the previous time step in QSTS simulations, and since the variation is minimal from time-step to time-step, the algorithm converges quickly. Thus, significant time reduction cannot be achieved from reducing the number of iterations.

3.2.2. Power flow approximations

In order to reduce the computational time, one alternative is to apply approximations to the power flow equations or to their solution methods. Some approximation methods consist of entirely linearizing the set of equations, while others find ways to approximate the Jacobian to decrease the CPU time spent on matrix factorization. Numerous power flow approximation methods are presented in the literature including but not limited to:

- i. Dishonest Newton: Keeps the same Newton-Raphson Jacobian matrix for a given number of iterations.
- ii. Fast decoupled power flow (FDPF): Assumes that line conductance and phase shifts between nodes are negligible and that voltage magnitude are close enough to not affect real power flow. As a result, the power flow equations are separated into two smaller independent systems with constant Jacobian matrices.
- iii. DC power flow: Mostly used for transmission systems due to their size and properties, this fully linear approximation ignores line conductance and reactive power flows.
- iv. Series impedance voltage drop approximation: Decoupled real and reactive power calculations, ignoring capacitance.
- v. LinDistFlow model: Based on the minimal spanning tree optimization problem [15], this model assumes no line losses on the feeder.

However, many of these approximations do not work well with multi-phase unbalanced distribution systems (e.g. due to their low X/R line ratio), and all power flow approximations suffer in certain conditions (whether in terms of accuracy or robustness). Since standard iterative power flow solvers typically converge in two iterations in QSTS simulations, the dishonest Jacobian method cannot provide significant computational time reduction, especially with linear equation solvers (e.g. PARDISO and KLU) splitting the symbolical and numerical factorization stages [16]. Other methods make assumptions, about either the voltage on the feeder or the reactive power flow, that introduce an error in the solution especially with reactive power flow injections (i.e. capacitor banks, volt/var inverters,...) or voltage regulating devices. This error can be reflected on the accuracy of various metrics reported by the QSTS simulation. Thus, the error introduced by power flow approximations poses a significant challenge in speeding up QSTS simulations.

Moreover, the interdependency between time-steps of the QSTS simulation (see Chapter 6) requires each time step to be solved chronologically which furthers the argument that much more important gains can be obtained by reducing the sheer number of time-steps to be solved as opposed to the CPU time of individual power flow solutions.

3.2.3. Improved power flow solving algorithm (CYME)

Computing a power flow solution in a commercial-grade environment does not only consist of the solution of the power flow equations. Database access, data exchange between the solver and the main application, initialization, and reporting of results all add up to a significant part of the computational time. Significant savings in CYME (sometimes more than 60%) are reported in [16] for the solution of individual power flows by optimizing various aspects of the algorithm. When applying these improvements to QSTS simulation, 10-fold reductions of the total simulation time have been observed. Although significant improvements have been made around the power flow solver and its implementation, there is still a need for additional speed improvements outside of how individual power flows are solved. The number of time-steps is still a challenge in speeding up the QSTS simulation.

4. CHALLENGE 2: CIRCUIT COMPLEXITY

4.1. Problem Statement

The set of power flow equations for an unbalanced, 3-phase system is nonlinear by nature. When considering various controller logics, the QSTS simulation becomes a discontinuous nonlinear system that can be very complex. Simplifying this system can be very challenging without having prior knowledge of how it behaves.

4.2. Discussion

4.2.1. Size of the distribution feeder

The computational time of the power flow solver is proportional to the number of nodes since each additional node increases the number of equations required to be solved. This correlation can be demonstrated by solving a yearlong QSTS simulation at 1-second resolution in OpenDSS using the KLU solver for three different circuits. The computational time versus the number of nodes is plotted in Figure 2.

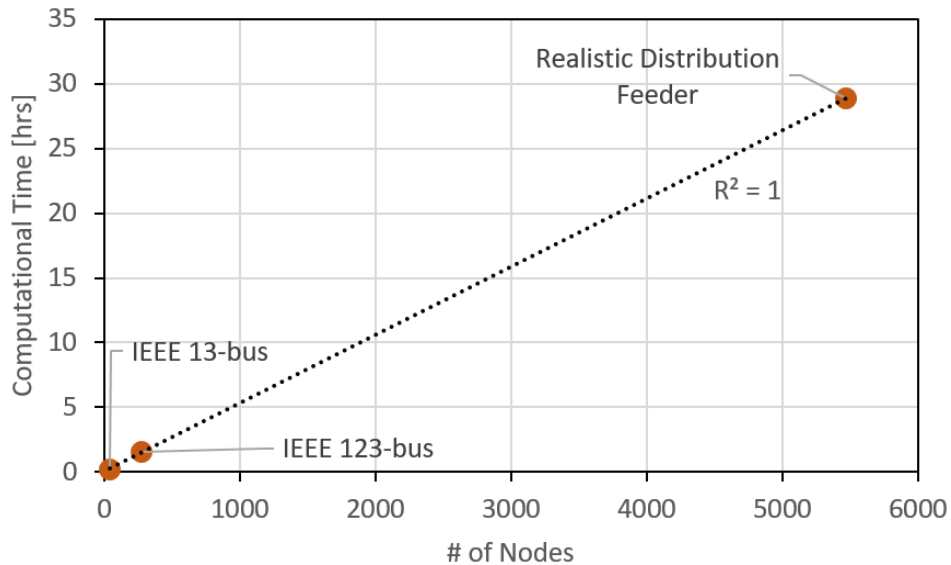


Figure 2. Computational time of a yearlong QSTS simulation at 1-second resolution in OpenDSS as a function of the number of nodes.

Since most distribution feeders have 1000+ buses [17], the size of the modeled distribution circuit has a significant impact on the speed of a QSTS simulation. Even with fast iterative solvers, additional work can be done to address the size of the feeder to reduce the computational speed.

4.2.2. System unpredictability

The nature of this discontinuous nonlinear system makes it especially challenging to predict how it will behave. For instance, the size of a PV system may or may not impact the operation of various controllers on a feeder. Furthermore, their impact is neither continuous nor linear as shown in Figure 3.

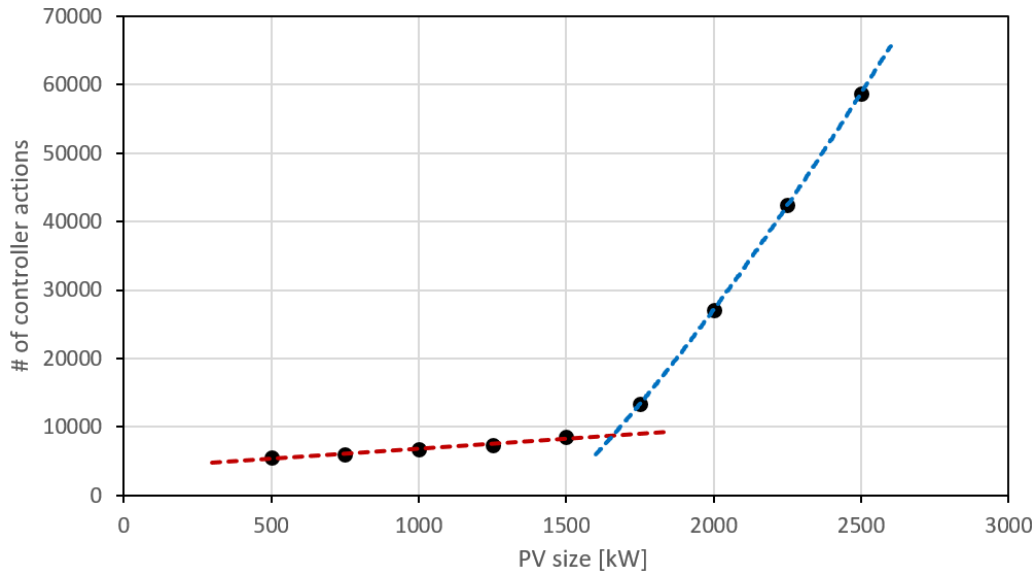


Figure 3. Total number of controller actions on a modified IEEE 13-bus test circuit with a centralized PV system of different sizes.

As shown in the figure above, the correlation between the number of controller actions and PV size is approximately linear only until it reaches ~1500kW. This is a trend that would have been very challenging to foresee based on the characteristics of the feeder.

The size of the PV system is not the only factor that causes unpredictability in the system. Its locations, whether it is distributed or centralized, the controller settings, the location of voltage regulating devices, their interactions, etc. are a small subset of the factors impacting the operation of a distribution feeder. The circuit complexity creates a challenge of unpredictability in the system that makes modeling QSTS simulation without going through each time-step challenging.

5. CHALLENGE 3: TIME DEPENDENCE BETWEEN TIME STEPS

5.1. Problem Statement

The time dependence in the control logic of certain distribution system devices requires the QSTS simulation to be solved chronologically. For instance, the delays and the deadbands in the controllers create a hysteresis in the state of the system. This hysteresis can be a challenge in reducing the computational time of QSTS simulations.

5.2. Discussion

Controller logics in some devices on a distribution feeder can have a time dependence either by design or by nature. Delays and deadbands are often incorporated in controllers (e.g. tap changers or capacitor banks) to ignore any short fluctuation in power flow and avoid oscillation in their operation. Delays can filter out high frequency variations while deadbands reduce oscillations caused by their own or other devices' operation. In addition to distribution voltage regulating devices, there can be many other devices on the distribution system with time-dependence, such as PV systems with advanced inverter controls and energy storage systems (ESS) state-of-charge (SOC) controls.

The benefit of the QSTS simulation solving power flow chronologically is that the time dependence in the different controllers can be modeled. Delays, deadbands, and SOC can easily be modeled similarly to how they are implemented in the field with if-statements and delay timers. For example, let us use the basic control logic of a capacitor bank on a distribution feeder. As the voltage at the point of interconnection varies, the controller logic monitors the voltage and takes an action if the signal is outside the thresholds once the delay timer has expired. A deadband separates the upper and lower thresholds to avoid fluctuation from the voltage variation created by action of the capacitor switching. A pseudo-code of the voltage-based control logic for a capacitor bank can be found in Algorithm 1 where $v_{control,m,t}$ is the control signal, $v_{ref,m}$ is the reference voltage, $v_{band,m}$ is the voltage deadband, $a_{m,t}$ is a delay aggregator, δ_m is the programmed delay, and $l_{m,t}$ is the state of the controllable device. Note that only two time-dependent variables are recorded between each time-steps: the previous state and the delay aggregator. Regarding ESS, a single variable for the SOC can be recorded between time steps to consider the physical limitation of the system.

When solving each time step chronologically, this hysteresis is easily modeled through the modeled logics. As the simulation advances second by second, the time dependence is naturally incorporated with the previous states and any delay timers. This may become a challenge for some computational time reduction approaches if the time steps are no longer solved chronologically. The controller hysteresis may not be accurately modeled or completely ignored which does not realistically represents the operation and state of the system.

Algorithm 1: Pseudo-code of Voltage-based Controller Logic

```
1: if  $|v_{control,m,t} - v_{ref,m}| \geq v_{band,m}/2$  :  
2:    $a_{m,t} = a_{m,t-1} + 1$ ,  
3:   if  $a_{m,t} < \delta_m$  :  
4:      $l_{m,t} = l_{m,t-1}$ ,  
5:   elseif  $a_{m,t} \geq \delta_m$  :  
6:     Controller action taken,  
7:   end  
8: else :  
9:    $l_{m,t} = l_{m,t-1}$ ,  
10:   $a_{m,t} = 0$ ,  
11: end
```

6. CHALLENGE 4: MULTIPLE VALID POWER FLOW SOLUTIONS

6.1. Problem Statement

Without the historical information about previous system states, multiple valid power flow solutions exist for given power injections on a feeder due to the deadbands and delays in controller logics. Therefore, correlating these power injections with the states of controllable devices becomes a challenge.

6.2. Discussion

Deadbands are often incorporated within controllers to reduce the oscillation from their own or other devices' operation. As a result, controllable devices on a feeder can have multiple valid states within their controller limits for a given power injection (e.g. for a given demand). For instance, in voltage regulating tap changers, system operators design the voltage deadband to include 3-5 tap positions within the thresholds to avoid oscillation. A voltage regulating tap changer aims to maintain the voltage within a specific threshold. Let $V_{regCtrl}$ denote the voltage signal of a regulator's controller. The regulator control keeps $V_{regCtrl}$ within the voltage band (V_{regMin}, V_{regMax}) by changing the tap position. When $V_{regCtrl}$ goes above V_{regMax} , the regulator control will trigger a tap change to move $V_{regCtrl}$ back within the deadband; similarly, when $V_{regCtrl}$ drops lower than V_{regMin} , the regulator will trigger an opposite tap change to also move $V_{regCtrl}$ back within the deadband. As the load increases downstream of the regulator, the voltage observed by the tap changers will decrease. A graphical model can be used to illustrate overlapping tap positions for a given demand. Generally speaking, $V_{regCtrl}$ is not linearly correlated with the load, however, in most distribution systems the error introduced by this linearized model is negligible. When we assume a linear correlation between $V_{regCtrl}$ and system load, we can model each tap position of the regulator as a solid line, as shown in Figure 4.

When the load increases from $L0$ to $L1$, $V_{regCtrl}$ will drop from $V0$ to $V1$; similarly, when the load decreases from $L0$ to $L2$, $V_{regCtrl}$ will increase from $V0$ to $V2$. In fact, as long as the load maintains within $L3$ and $L4$, no tap action will be triggered. However, when the system load moves beyond $L3$ and $L4$, a tap action will be triggered and the tap will move to the adjacent tap position, which corresponds to the adjacent lines in the graphic model.

When these solid lines overlap each other, one cannot associate a load level to a specific tap position without considering its state at a previous time step. In practice, these solid lines will overlap 3-5 times for a given load. This discontinuity in the relationship between load and system states can become a challenge in approximating control logic models.

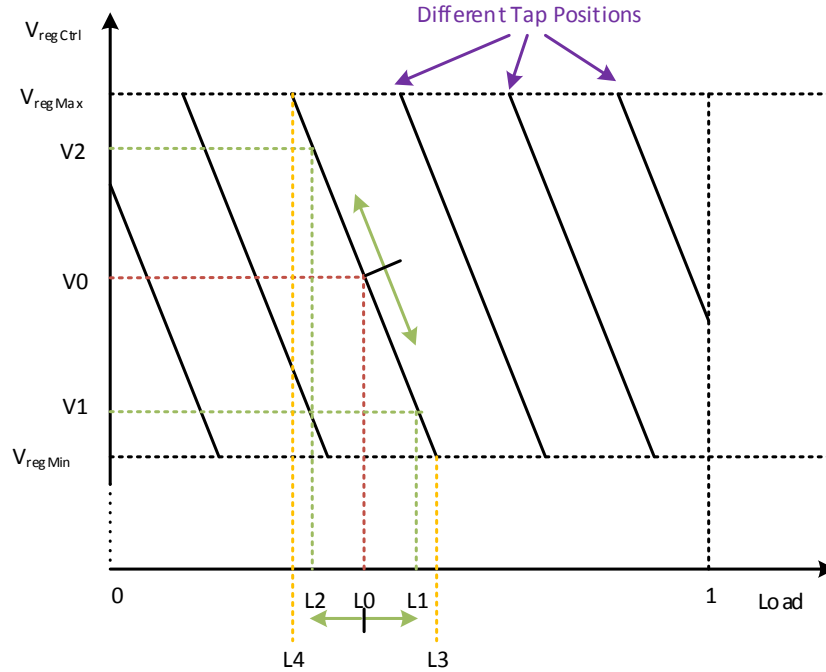


Figure 4. Illustrative representation of regulator control input voltage vs. system load.

Because the deadbands in controllers create a hysteresis in the state of the system, approximating control logic models can become extremely complex without modeling the actual logic of the controllers. Models based on power injections cannot be used when controllers are considered since multiple discrete system states would be valid for the same power injections. For example, a machine learning model, which seeks to establish a one to one mapping between the QSTS inputs and outputs, is not able to learn the correlation because the same inputs will yield multiple valid possible power flow solutions. This challenge can present a problem for any new QSTS algorithms that do not track the system states through time. The most intuitive solution to eliminate the effect of the multiple valid solutions is to introduce time dependence and time correlation, which itself becomes a new challenge that can be computationally cumbersome to achieve an accurate representation of the operation of the system.

7. CHALLENGE 5: CONTROLLABLE ELEMENT INTERACTIONS

7.1. Problem Statement

Controllable elements placed on the same phase will interact with one another. Because of their deadbands, an action in one controller caused by a small voltage approximation error in the power flow solution can create false oscillations in other controllers before it can be cleared.

7.2. Discussion

7.2.1. Oscillations

Multiple voltage regulating devices can be placed on the same circuit, especially on long radial distribution feeders. Deadbands and delays in the controller of each device are coordinated to avoid continuous oscillations between devices. However, their coordination becomes complex when PV introduce large fluctuations in power injections in the circuit, which can create reverse power flow. This challenge is illustrated with a modified IEEE 13-bus test circuit with 10% and 40% PV penetration (Figure 5). Two voltage regulating devices are considered: a voltage regulating tap changer at the substation and a capacitor bank near the PV system.

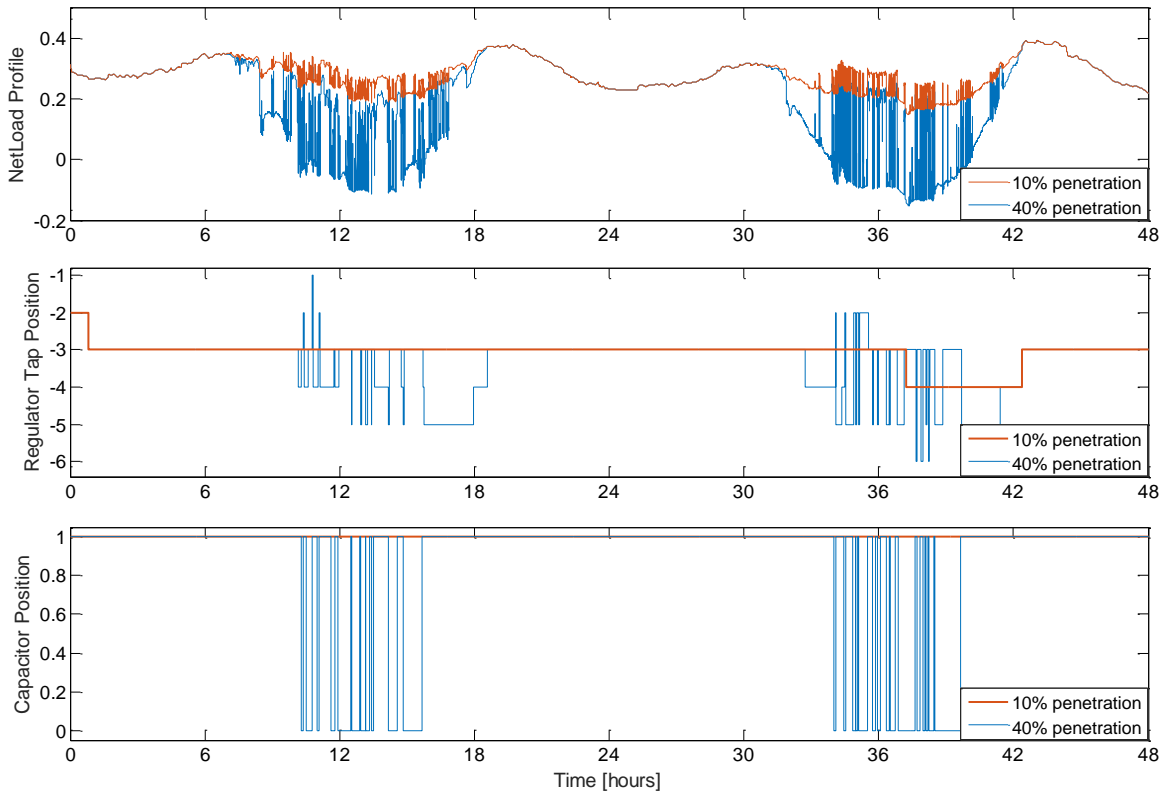


Figure 5. Plot of the net load at the substation (normalized to peak load), regulator tap position and capacitor position over a 2-days period for a system with 10% and 40% penetration of PV. The regulator has 125 tap actions (instead of 3) and the capacitor banks has 52 actions (instead of 0) with the increase in PV penetration.

As expected, the tap changer will regulate the voltage to follow the daily variation of the demand. In the 10% simulation, the controller of the capacitor bank does not operate because of its delay being longer (30 sec.) than that of the tap changer (15 sec.) allowing the voltage to be regulated before the capacitor bank operates. The daily operation of the controllers is very different when a larger PV system is considered. In the 40% simulation, the capacitor bank will operate to regulate the voltage at the end of the feeder. This operation will trigger the tap changer to operate in response to the capacitor state because of the reactive power injection variation. Since the capacitor bank is more sensitive to the PV system, its operation will increase and consequently increase the operation of the tap changer.

Modeling the interactions between the operations of these voltage regulating devices can be difficult to predict especially when they interact with one another. The deadbands and delays in the controller logics are designed to avoid oscillation under specific conditions. However, new interconnections can disrupt this balance and create emergent behaviors with considerable impacts on the feeder.

7.2.2. Cascading error

Another aspect of the challenge with controller interactions is cascading errors. Because of the deadbands in the controllers, the controllable element may trigger a change and remain in that state for an extended period of time. As a result, the operation of other controllers can be significantly impacted by it. For example, the state of a capacitor bank, which is a reactive power injecting device, can impact the operation of an upstream tap changer. Because of the multiple valid power flow solutions discussed in Chapter 6, under the same power injection conditions, the operation of the tap changers can increase or decrease dramatically based on the state of the capacitor bank. In Figure 6, a simulation is conducted where a single regulator action is neglected and as a result triggers the capacitor to operate. This single error produces a completely different series of controller events over the following few hours causing the tap changers to record additional actions before returning to identical system states.

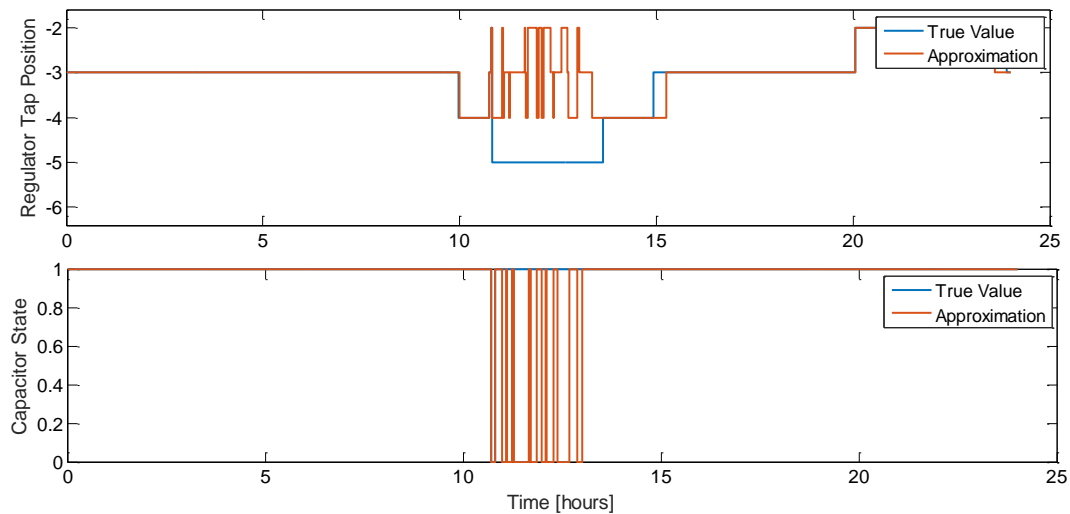


Figure 6. States of voltage regulating devices over a 24 hour period demonstrating how the interaction between devices can create cascading errors with excess actions.

In this simulation, the cascading error only took approximately four hours to disappear but it could have easily taken a few simulation days. Speeding the QSTS simulation without going through the controller logics at each time-step is challenging because of these controller interactions. A small approximating error in the power flow solution can create a controller action that can impact how another controller has operated over a period. This is a significant challenge that affects most if not all computational time reduction approaches.

8. CHALLENGE 6: ACCURATE ANALYSIS FOR EXTENDED TIME-HORIZON SIMULATIONS

8.1. Problem Statement

To characterize the impact of a new resource on a feeder, various metrics (e.g. number of tap actions or voltage violations) can be computed a posteriori based on the time-series solutions. However, a large amount of data is often required to fully understand its impact. For instance, monitoring voltage violations would require recording voltage quantities for all the nodes in the system for all the time points (e.g. 31 million time points times 10k unbalanced nodes). In addition, the accuracy of each reported metric may be impacted differently based on the approach taken to reduce the computational burden.

8.2. Discussion

8.2.1. Data logging requirement

The amount of data to be recorded is dependent on the objective behind the QSTS simulation, whether it is to study the impacts on voltage quality or the operation of controllable devices. The analysis from a QSTS simulation can be categorized into two types of data: discrete metrics or time series measurements.

Discrete metrics, such as number of controller actions or total power losses, can be recorded as aggregating values at each time-steps or later computed by recording time-series data to process a posteriori. Obviously, there is an advantage for both approaches. Only recording aggregated values does not have a significant memory requirement but will not allow further analysis besides the final discrete metric. On the other hand, recording time-series data requires significant memory but allows post simulation analysis.

Recording data at each time-step can increase the computational time either because of the sheer amount of data (i.e. voltage magnitude) or because of a necessary logic (i.e. tap change if-statement). More specifically, recording time-series voltage measurements for large distribution feeders (500+ buses) may not be possible without running the simulation in sequences. When the power flow solver is contained in its own dynamic-link library (DLL), non-negligible computational overhead may also result from the transfer of large amount of data at each time-step between the solver and the main application.

The purpose behind running a QSTS simulation is to understand the operation of a distribution feeder under certain conditions. However, it may be challenging to provide a clear understanding of the system without having multiple metrics and/or time-series measurements to analyze. Data management can become a challenge based on the approach taken to reduce the computational time.

8.2.2. Metric accuracy

Reducing the computational time of a QSTS simulation can be done multiple ways: increasing step size, decreasing time-horizon, circuit reduction, etc. However, the accuracy of some reported metrics could be negatively impacted in the process. Each approach used to reduce the computational speed are based on assumptions that may or may not impact the accuracy of a metric. For instance, the increased step-size approach assumes that a single time-step represents multiple others or the shorter time-horizon approach assumes that a portion of the year is representative of the rest of the yearlong simulation.

Because approaches can compute metrics differently, the accuracy of certain metrics may be impacted in different ways. Some metrics can be time sensitive, voltage sensitive, or neither. For instance, the total number of controller actions recorded in a yearlong simulation is voltage- and time-sensitive while power losses in the system is neither. Power losses can be estimated with negligible error without having to solve each time-step chronologically or accurate voltage profiles. Furthermore, the number of controller actions is a discrete metric based on the hysteresis of the controllers while power losses is not.

Increasing the time-step size is the most apparent approach in reducing computational time. Running the yearlong simulation at a 100-second resolution instead of 1-second will provide a 99% reduction in computational time. However, this approach introduces an error in reported metrics that is time-sensitive. For example, the total number of controller actions by the tap changer will not be accurately reported but power losses will see little impact (Figure 7).

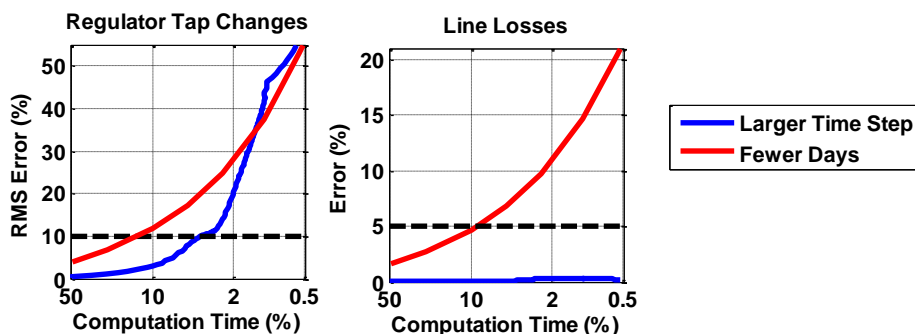


Figure 7. States of voltage regulating device over a 24 hour period demonstrating how the capacitor state can create excess actions by the tap changers [5]

The error associated with the larger time-step size is due to the delays in the controllers. As soon as the time-step size approaches or exceeds the length of the delay, tap actions may or may not be recorded which can accumulate to a poor accuracy in reported metrics (See Challenge 5).

Reporting various metrics accurately is especially challenging given that this temporal system is a discontinuous and nonlinear system. While considering different approaches to reduce the computational time of QSTS simulations, it is important to retain an acceptable accuracy in the reported metrics.

9. ONGOING RESEARCH

Due to the increasing need of QSTS simulations for studying the impacts of high penetration PV scenarios and new smart grid technologies and controls, improving the speed of the QSTS simulation is a major ongoing research area. While speeding up QSTS is not an easy problem to solve, there have already been significant improvements made in prototype demonstrations. All new QSTS algorithms developed in current and future research will have to overcome each of the challenges highlighted in this report.

Ongoing research in this area is investigating approaches such as: clustering days, intelligent sampling, variable time-step, event-based simulation, vector quantization, circuit reduction, and temporal and spatial parallelization.

The issue of the number power flows in a QSTS simulation (Challenge 1) can be addressed by reducing the number of time-step the simulation must go through. The clustering-days approach reduces the time-horizon of simulation by clustering days with similar load and PV profile [18], [19]. While large time-steps in QSTS simulation can create significant errors [5], variable time-step algorithms can be used to intelligently modify the time-step size around key periods of interest and high variability [20], [21].

The complexity of the distribution system analysis and unpredictability (Challenge 2) can be solved by creating a physics-based electrically equivalent reduced-order model for the pieces of the system of interest using circuit reduction [22]. Key buses of interest and voltage regulation equipment can remain in the reduced model while reducing the number of total buses.

As discussed in Section 3.2.2, the computational time of the QSTS simulation can be reduced with different power flow approximations to avoid full nonlinear iterative power flow solutions, but this suffers from the discontinuous nature of the circuit discussed in Challenge 2. Because the QSTS simulation is nonlinear (power flow equations) and discontinuous (controller logic), a discontinuous linear approximation can be used to speed up the algorithm by modeling a separate linear model for each topology and discrete state of the distribution system. Because of the time-dependence (Challenge 3), the simulation must still be solved in sequential order, but the combination of these linear approximations can be used to solve the time-series using discrete event-based simulation [23].

Because of the multiple valid power flow solutions (Challenge 4), the system topology and state must always be accounted for in new QSTS algorithms. For example, vector quantization [24] clusters similar time-steps with respect to the load and PV profiles as well as the states of the controllable elements on the system. The control logic is then handled outside the rapid QSTS algorithms, similar to what is shown in Figure 1.

The computational speed can also be reduced by increasing the computational power to solve the simulation. The system can either be sectioned spatially [25] or temporally [26] to be solved in parallel on separate computer cores.

10. CONCLUSION

The rapid increase in penetration of distributed energy resources has created a need for comprehensive interconnection analysis and for determining optimal control solutions for utility operations that can capture any emergent behaviors between devices [27]. Quasi-static time-series (QSTS) simulations provide a temporal dimension to the analysis that allows the study of time-sensitive impacts on a distribution feeder (e.g. excessive number of voltage regulator tap changes). By modeling controller logics (e.g. voltage regulating tap changers) or system characteristics (e.g. grid topology or battery state-of-charge), their impact on the daily operation of the system can be studied realistically. However, QSTS simulation has not been widely used in interconnection analyses because of their computational burden. In this report, the unique challenges regarding reducing the computational time of QSTS distribution system simulation are presented.

First, even with fast iterative solvers, solving the unbalanced three-phased power flow equations millions of times requires significant computational power. Second, this nonlinear (power flow equations) and discontinuous (control logics) system cannot be easily simplified to study its unpredictable behavior. Third, the logic in some controllers introduce a time dependence between time-steps requiring the QSTS simulation to be solved chronologically, creating a hysteresis in the system states. Fourth, the deadbands in the controllers can have multiple valid states within their limits, making the correlation between power injections and system states challenging. Fifth, because of controllable element interactions, an erratic action in one controller caused by a small voltage approximation error can create oscillations in other controllers before it is cleared. Sixth, the accuracy of each metric reported by the QSTS simulation can be impacted differently based on the approach taken to reduce the computational burden.

This report highlighted the most relevant challenges to reducing the computational speed of QSTS simulation: number of power flows to solve, circuit complexity, multiple valid power flow solutions, time dependence between time-steps, controllable element interactions, and extensive accurate simulation analysis. This power system research direction differs from the conventional research directions (OPF, unit-commitment, etc.) with its temporal aspect and the consideration of voltage regulating devices. A number of ongoing research efforts are addressing these challenges and preliminary results are already promising.

11. REFERENCES

- [1] IEEE P1547.7 D110, “Draft Guide to Conducting Distribution Impact Studies for Distributed Resource Interconnection,” 2013.
- [2] B. A. Mather, “Quasi-static time-series test feeder for PV integration analysis on distribution systems,” *IEEE Power Energy Soc. Gen. Meet.*, pp. 1–8, 2012.
- [3] R. J. Broderick, J. E. Quiroz, M. J. Reno, Abraham Ellis, J. Smith, and R. Dugan, “Time Series Power Flow Analysis for Distribution Connected PV Generation,” SAND2013-0537, Albuquerque, NM, 2013.
- [4] J. E. Quiroz, M. J. Reno, and R. J. Broderick, “Time series simulation of voltage regulation device control modes,” in *IEEE Photovoltaic Specialists Conference*, 2013, pp. 1700–1705.
- [5] M. J. Reno, J. Deboever, and B. A. Mather, “Motivation and Requirements for Quasi-Static Time Series (QSTS) for Distribution System Analysis,” in *IEEE PES General Meeting*, 2017.
- [6] M. Lave, M. J. Reno, and R. J. Broderick, “Characterizing local high-frequency solar variability and its impact to distribution studies,” *Sol. Energy*, vol. 118, pp. 327–337, 2015.
- [7] M. Kleinberg, J. Harrison, and N. Mirhosseini, “Using energy storage to mitigate PV impacts on distribution feeders,” in *IEEE PES Innovative Smart Grid Technologies (ISGT)*, 2014.
- [8] M. J. Reno, K. Coogan, R. Broderick, and S. Grijalva, “Reduction of distribution feeders for simplified PV impact studies,” in *IEEE Photovoltaic Specialists Conference*, 2013, pp. 2337–2342.
- [9] D. Montenegro, G. A. Ramos, and S. Bacha, “A-Diakoptics for the Multicore Sequential-Time Simulation of Microgrids Within Large Distribution Systems,” *IEEE Trans. Smart Grid*, pp. 1–9, 2015.
- [10] C. D. López, “Thesis: Shortening time-series power flow simulations for cost-benefit analysis of LV network operation with PV feed-in,” Uppsala Universitet, 2015.
- [11] A. Pagnetti and G. Delille, “A simple and efficient method for fast analysis of renewable generation connection to active distribution networks,” *Electr. Power Syst. Res.*, vol. 125, pp. 133–140, 2015.
- [12] W. H. Kersting, *Distribution system modeling and analysis*, 3rd ed. Las Cruces, NM: CRC Press, 2012.
- [13] J. B. Ward and H. W. Hale, “Digital Computer Solution of Power-Flow Problems,” *AIEE Trans. (Power Appl. Syst.)*, vol. 75, pp. 398–404, 1956.
- [14] R. C. Dugan, “OpenDSS Manual,” 2016.
- [15] M. E. Baran and F. F. Wu, “Network reconfiguration in distribution systems for loss reduction and load balancing,” *IEEE Trans. Power Deliv.*, vol. 4, no. 2, pp. 1401–1407, 1989.
- [16] F. Therrien, M. Belletête, J. Lacroix, and M. J. Reno, “Algorithmic Aspects of a Commercial-Grade Distribution System Load Flow Engine,” in *IEEE Photovoltaic Specialists Conference (PVSC)*, 2017.
- [17] R. J. Broderick, J. R. Williams, and K. Munoz-Ramos, “Clustering Method and Representative Feeder Selection for the California Solar Initiative,” SAND2014-1443, Albuquerque, NM, 2014.

- [18] J. Galtieri and M. J. Reno, "Intelligent Sampling of Periods for Reduced Computational Time of Time Series Analysis of PV Impacts on the Distribution System," in *IEEE Photovoltaic Specialists Conference (PVSC)*, 2017.
- [19] M. J. Reno, R. J. Broderick, and L. Blakely, "Machine Learning for Rapid QSTS Simulations using Neural Networks," in *IEEE Photovoltaic Specialists Conference (PVSC)*, 2017.
- [20] M. J. Reno and R. J. Broderick, "Predetermined Time-Step Solver for Rapid Quasi-Static Time Series (QSTS) of Distribution Systems," in *IEEE Innovative Smart Grid Technologies (ISGT)*, 2017.
- [21] B. A. Mather, "Fast Determination of Distribution-Connected PV Impacts Using a Variable Time-Step Quasi-Static Time-Series Approach," in *IEEE Photovoltaic Specialists Conference (PVSC)*, 2017.
- [22] Z. K. Pecanak, V. R. Disfani, M. J. Reno, and J. Kleissl, "Multiphase Distribution Feeder Reduction," *IEEE Trans. Power Syst.*, 2017.
- [23] X. Zhang, S. Grijalva, M. J. Reno, J. Deboever, and R. J. Broderick, "A Fast Quasi-Static Time Series (QSTS) Simulation Method for PV Impact Studies Using Voltage Sensitivities of Controllable Elements," in *IEEE Photovoltaic Specialists Conference (PVSC)*, 2017.
- [24] J. Deboever, S. Grijalva, M. J. Reno, X. Zhang, and R. J. Broderick, "Scalability of the Vector Quantization Approach for Fast QSTS Simulation for PV Impact Studies," in *IEEE Photovoltaic Specialists Conference (PVSC)*, 2017.
- [25] D. Montenegro, R. C. Dugan, and M. J. Reno, "Open Source Tools for High Performance Quasi-Static Time-Series Simulation Using Parallel Processing," in *IEEE Photovoltaic Specialists Conference (PVSC)*, 2017.
- [26] R. Hunsberger and B. A. Mather, "Temporal Decomposition of Distribution System Quasi-Static Time-Series Simulation," in *IEEE PES General Meeting*, 2017.
- [27] B. Palmintier, R. Broderick, B. Mather, M. Coddington, K. Baker, F. Ding, M. Reno, M. Lave, and A. Bharatkumar, "On the Path to SunShot: Emerging Issues and Challenges in Integrating Solar with the Distribution System," National Renewable Energy Laboratory, NREL/TP-5D00-65331, 2016.

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